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# Land Surface Temperature Measurements from EOS MODIS Data

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A cloud-screen scheme with constraints on spatial and temporal variations in LSTs is developed to screen off the cloud-contaminated LSTs in the MODIS LST products. This scheme is applied to the V3 and V4 1km MODIS LST (MOD11A1) products in Lake Tahoe and Namco (a lake in Tibet) in 2002 to show the impact of using the MODIS cloudmask (MOD35) product in different ways: processing lake and river pixels only in clear-sky condition at the 99% confidence level in V3 and at equal to or larger than the 66% confidence level in V4. The test study unveils that cloud-contaminated LSTs exist even at pixels defined by MOD35 in clear-sky conditions at the 99% confidence level and that these contaminated LSTs can be removed by the cloud-screen scheme. The cloud-screen scheme is also applied to the V4 5km MODIS LST (MOD11B1) product at test sites in lakes, snow/ice, Amazon rain forest and semi-arid regions, indicating that the MODIS cloudmask needs to be improved. After screening off the cloud-contaminated LSTs, the time sequence of the MODIS LST products clearly shows the freezing and lake-ice melting in Namco, and the snow/ice melting period in Greenland. The MOD11B1 product is validated through comparing the LSTs retrieved by the day/night method to the LSTs in the MOD11A1 product that has been validated with in-situ measurement data in lakes, snow and agricultural fields in field campaigns conducted in 2000-2003. The mean and standard deviation values of the differences between the LSTs retrieved by these two methods are 0.03K and 0.6K in Lake Superior and Lake Tahoe, 0.3K and 0.6K in Namco, and -0.4K and 0.97K in a snow/ice site at 63.0°N, 47.8°W in Greenland. The MOD11B1 product is also validated with ground-based measurement data at Gaize (32.3°N, 84.06°E, 4420m above sea level) in the western Tibet plateau through comparing the broadband emissivity calculated from the band emissivities in the MOD11B1 product to the broadband emissivity calculated from the ground measurements in 2001-2003 (the mean and standard deviation are 0.001 and 0.013, respectively). The statistics of clear-sky days in the LSTs at latitude/longitude 5.0°S, 65.0°W in Amazon rain forest in V4 1km and 5km MODIS LST (MOD11A1 and MOD11B1) products in 2001-2003 indicated that the day/night LST algorithm can be used globally as long as pairs of clear-sky day and night MODIS observations exist within a reasonable period of days.

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Z. Wan, Y. Zhang, Q. Zhang, and Z.-L. Li, Quality assessment and validation of the MODIS global land-surface temperature, *Int. J. Remote Sens.*, Vol. 25, No. 1, 261-274, 2004.

## 1. INTRODUCTION

This report addresses three major concerns in the MODIS LST user community: (1) what is the impact of the MODIS cloudmask on the MODIS LST products and how to screen off the cloud-contaminated LSTs? (2) how to validate the 5km MODIS LST product? and (3) is it appropriate to apply the day/night LST algorithm in regions such as tropical rain forests where there are less clear-sky days?

## 2. CLOUD-SCREENING SCHEME

In the MODIS LST product, LST is defined by the radiation emitted by the land surface observed by MODIS at the instant viewing angle. The land surface is canopy in vegetated areas or soil surface in bared areas, and whatever objects observed by MODIS thermal infrared (TIR) sensors. One of the basic considerations for the MODIS LST product is to retrieve LST from MODIS TIR data only in clear-sky conditions so that LST is not mixed with cloud-top temperature. Because TIR signals cannot penetrate thick clouds, it is difficult to correct the effect of thin clouds on the TIR signals without knowing the exact optical depth of thin clouds, and the probability of cloudy conditions is often larger than 50% at the regional and global scales, cloudy pixels must be skipped in the LST processing (giving a fillvalue, zero, LST to the cloudy pixels). The LST retrieval in a MODIS swath is constrained to land and inland water pixels that have nominal Level 1B radiance data, are in clear-sky conditions at a 99% confidence defined in the MODIS cloud-mask product (MOD35). In the V4 LST processing, LST retrieval is made for lake and river pixels at clear-sky conditions with a 66% and higher confidence defined in MOD35 and for other land pixels in clear-sky at a 99% confidence, in order to improve the consistency between the spatial LST distributions over lakes and their surrounding lands. The radiance values of those pixels processed in the LST retrieval with the generalized split-window algorithm (Wan and Dozier, 1996) for the level-2 LST product (MOD11_L2) are also stored in interim files through mapping the pixels onto 5km grids in the integerized sinusoidal (in V3) or sinusoidal projection (in V4) for the consequent simultaneous retrieval of land-surface emissivities and temperatures from pairs of day and night MODIS observations with the day/night LST algorithm (Wan and Li, 1997).

It has been a known issue that there are cloud-contaminated LSTs in the MODIS LST product. Although the state-of-art techniques based on multiple MODIS bands have been used in the MODIS cloud mask product (MOD35_L2), and the MODIS LST PGE produces LSTs only for the clear-sky land pixels at the highest confidence (99%) defined by MOD35_L2, there are still some possibilities that MODIS LSTs are contaminated with cloud effects because of the difficulty to accurately discriminate true clear-sky pixels from cloud pixels and pixels contaminated with sub-pixel clouds. A double-screen scheme (Wan et al., 2002) has been used to remove the cloud-contaminated LSTs in the extreme conditions at the global scale in the generation of the daily global LST product at 0.05$^\circ$ climate model grids (CMG). For individual pixel and grid at a given location, we developed another cloud-screen scheme to remove cloud-contaminated LSTs in the MODIS LST level-2 (MOD11_L2) and level-3 (MOD11A1, MOD11A2, and MOD11B1). We define a target grid (or pixel) with its center at the given latitude/longitude location and its size equal to the nearby grid (or pixel). The LST value for the target grid at homogeneous sites can be interpolated from the values of its four surrounding grids. With constraints on spatial and temporal variations in LSTs, the cloud-screen scheme consists of three options to remove cloud-contaminated LSTs:

A. non-fillvalue LST exists at less than N grids.

B. the maximum difference between the LST values at these grids is larger than $(\delta T)_S$.

C. step 1: remove worst LSTs in the time sequence of LSTs if its difference from the 32-day maximum value is larger than $4\times(\delta T)_T$, or its difference from the 8-day maximum value is larger than $3\times(\delta T)_T$, and then calculate 8-day averaged values;

step 2: remove LSTs if its difference from the 8-day averaged value is larger $(\delta T)_T$.

We evaluate the cloud-screen scheme in large lakes first because in-situ and satellite data indicate that the surface temperature in large lakes is quite homogeneous spatially and varies with time slowly. (Irbe, 1992; Malm and Jönsson, 1994; Malm and Zilitinkevich, 1994). Lake Tahoe spans California and Nevada at elevation of 1987m above sea level, with 35km long, 19km wide, and average depth of 488m, not freezing around the year. Namco (lake) in Tibet is at elevation of 4530m above sea level, about 80km long and 50km wide, average depth of 40m, freezing in the winter. If any LST value in Lake Tahoe is below the freezing point, 273.15K, it is definitedly cloud-contaminated. And similarly for the LST value in Namco in the non-freezing seasons.

This scheme is applied to the V3 and V4 1km MODIS LST (MOD11A1) products in Lake Tahoe and Namco in 2002 to show the impact of using the MODIS cloudmask (MOD35) product in different ways: processing lake and river pixels only in clear-sky condition at the 99% confidence level in V3 and at equal to or larger than the 66% confidence level in V4. The results are shown in Table I. A location near the centers of Lake Tahoe and Namco is selected. In the first row of the table body, N = 1 without $(\delta T)_S$ and $(\delta T)_T$ options means that only the grid covering the target point is considered, there are 174 days and 39 nights with non-fillvalue LST in Lake Tahoe in totally 351 days in 2002 when V3 MOD11A1 product is available. The V4 MOD11A1 product is available for 355 days. There are 257 days and 202 nights with non-fillvalue LSTs. The daytime and nighttime LSTs in V3 and V4 are shown in the top of Figure 1. One nighttime LST in V3 (where all LST pixels in clear-sky conditions at the 99% confidence level defined by MOD35) is around 264K. And there are more daytime and nighttime LSTs below 273.15K in V4. As shown in the second row of Table I, N = 4 means that the LST will be removed as cloud-contaminated value if any grid in the four neighboring grids is in cloudy conditions (with fillvalue for LST). In the third row, N = 4 and a spatial variation constraint of $(\delta T)_S$ = 3.0K is applied. In the fourth row, N = 4 and both spatial and temporal constraints of 3.0K are applied. After applying the cloud-screen scheme with these options, the daytime and nighttime LSTs are above 273.15K as shown in the bottom of Figure 1. Similarly, the results for Namco (at 4530m above sea level) are shown in the right side of Table I and Figure 2. The top plot indicates that the daytime and nighttime LSTs in V3 and V4 spread in a wide range from 230K to 290K. It is obvious that the lake surface temperature could not change so much in a few days. This plot clearly indicates that the current MODIS cloudmask does not work well in high elevation conditions. After applying the cloud-screen scheme with N = 4 and spatial and temporal constraints of 3K, the V4 daytime and nighttime LSTs are shown in the bottom plot of Figure 2. The time sequence of the LSTs clearly shows the days of freezing and lake-ice melting in Namco (the horizontal dash line presents freezing temperature of 273.15K). Comparing the numbers of LSTs in the first row and the fourth row (219 vs 177 for V4 daytime LSTs and 223 vs 135 for V4 nighttime LSTs) indicates that the cloud-contaminated LSTs account for about 20% in daytime and 40% in nighttime. There is a trade-off in choosing the values for the spatial and temporal variation constraints. The smaller the values, the stronger the constraints, thus more LSTs will be removed. If the constraints are too strong, some really clear-sky LSTs may be also removed. If the constraints are too weak, some really cloud-contaminated LSTs cannot be removed. Test indicates that a reasonable constraint value can be selected in the range of 2-4K for large lakes. In the last row of Table I, N = 1 and only a temporal constraint of 3K is applied. This option should be used near ocean and lake coastal lines, and in lands where the spatial variation in LSTs is large because near boundaries of different land types. This option works fine in the cases of Lake Tahoe and Namco as long as there are enough points in the time sequence of LSTs. The V3 nighttime LST around 264K cannot be removed with the temporal option because it is the only nighttime LST in the first four months in V3.

The cloud-screen scheme is also applied to the V4 5km MODIS LST (MOD11B1) product in 2003 at test sites in lakes, snow/ice, and semi-arid regions. The results are shown in Table II. Considering the different years and the different grid sizes in MOD11A1 (1km) and MOD11B1 (5km), the numbers of LSTs in the Lake Tahoe and Namco cases before and after applying the cloud-screen scheme are different but they are comparable. Besides Lake Tahoe and Namco (lake), we also applied the cloud-screen scheme to the MOD11B1 product in 2003 at latitude 47.25$^\circ$N and longitude 87.22$^\circ$W in the middle of Lake Superior, Michigan. According to CTV.ca News on 03/11/2003 titled "Great Lakes Article: Great Lakes freeze delays shipping season" (http://www.greatlakesdirectory.org/on/031103__great_lakes.htm), "For the first time in years, three of the Great Lakes (Lake Superior, Lake Huron, and Lake Erie) have frozen over shoreline-to-shoreline." Lake Erie, the shallowest of the lakes, often freezes from shore to shore. But Superior and Huron are both among the world’s five largest lakes, and don’t freeze over often because their enormous volumes of water rarely get cold enough. Before applying the cloud-screen scheme, the daytime and nighttime LSTs in the MOD11B1 product are shown in the top plot of Figure 3. We can see that there are several LSTs below 273.15K in the non-freezing season (approximately after Julian days 120). The values of parameters N, $(\delta T)_S$ and $(\delta T)_T$ in applying the cloud-screen scheme to this case are 4, 3K, and 5K before Julian 121, and 4, 3K, and 3K starting from Julian day 121, respectively. If we use the same parameters (4, 3K, 3K) for the whole year, three daytime LSTs and three nighttime LSTs below 268K (in the bottom plot) would be removed. These six LST values seem reasonable for the lake ice in the cold Spring. Note that the numbers of LSTs are given in the parentheses in the plots but not in Table II.

Different values are used in the spatial and temporal constraints on daytime and nighttime LSTs at the snow/ice site in Greenland, and at Gaize in the semi-arid region in Tibet. The daytime and nighttime LSTs at a snow/ice site (63.0° N, 47.8° W) in Greenland in 2003 are shown in Figure 4. There is no daytime LST in the first 50 days and last 60 days of the year, and no nighttime LST in the first 50 days and last 30 days because of the two requirements in the day/night LST algorithm: solar zenith angle cannot be larger than 65° and the time difference in the pair of day and night MODIS observations cannot be larger than 32 days. Before applying the cloud-screen scheme, the daytime and nighttime LSTs shown in the top plot of Figure 4 are not well separated, and some nighttime LST values are too low in the summer. After applying the scheme, the daytime LSTs are well separated from nighttime LSTs and there are daytime LSTs within 273.15 ± 1 K in the period of Julian days from 150-240. This time sequence of daytime LSTs clearly shows the snow/ice melting season in Greenland. There is no daytime LST larger than 274.15K at the snow/ice site, indicating that the accuracy of the LSTs at the snow/ice site in the MOD11B1 product is better than 1K. The cloud-screen scheme is also validated in the comparison between MODIS LST data and ground-based measurement data at the Gaize automatic weather station (32.3° N, 84.06° E, 4420m above sea level) in the western Tibet plateau (Kaicun Wang, personal communication). The numbers in Table II indicate that the cloud-contaminated LSTs account for about 30% in daytime and 10% in nighttime at the Gaize site.

Although the cloud-contaminated LSTs in the MOD11A1 and MOD11B1 products can be removed with the cloud-screen scheme, it will hold the release of daily MODIS LST products for more than 32 days. Users would not like such long delay. It would also be a big problem for the MODIS product generation system to stage the daily LST products for so many days for the cloud-screen past-processing. The best approach is to do a good job from the beginning. It requires a significant improvement of the current MODIS cloudmask product. In the generation of the current MODIS cloudmask product, the spectral tests in ocean and inland water use the same thresholds. The variations in land surface elevation and emissivities are not considered in the thresholds for land. In order to improve the MODIS cloudmask product, smart thresholds, which depend on land surface elevation and thermal properties, may be needed.

## 3. Validation of the MOD11B1 Product

In the past four years, a large number of field campaigns have been conducted in lakes, grassland, snow field, and agricultural fields to validate the MODIS level-2 (MOD11_L2) and level-3 1km (MOD11A1) products retrieved by the generalized split-window algorithm (Wan et al., 2002, 2004). For the 5km MOD11B1 product retrieved by the day/night LST algorithm, validation activities limit to only two cases, one for the emissivities in the Sahara desert, another for the emissivities in Caspian Sea (Wan et al., 2004). It is very difficult to find test sites large and homogeneous enough to make ground-based measurement of the surface emissivity and LST at the 5km scale.

Once the 1km LST (MOD11A1) product is relatively well validated, it is more practical to validate the 5km LST (MOD11B1) product indirectly through comparing the 5km-resolution LSTs in MOD11B1 to the LSTs in MOD11A1 aggregated to 5km grids (that are also stored in the MOD11B1 product). After applying the cloud-screen scheme to the MOD11B1 product in 2003 at test sites in lakes, snow/ice, Amazon rain forest and semi-arid regions, we made comparisons of LSTs retrieved from the two algorithms, as shown in Figure 5 for Lake Superior, Figure 6 for the Lake Tahoe and Namco sites, and in Figure 7 for the snow/ice site in Greenland and the semi-arid site in Gaize, Tibet. The mean and standard deviation values of the differences between the LSTs retrieved from the split-window algorithm and the LSTs retrieved from the day/night algorithm are shown in Table III. In the Lake Superior case, the mean and standard deviations are 0.02K and 0.54K for the daytime LSTs, 0.06K and 0.55K for nighttime LSTs, and 0.03K and 0.55K for daytime and nighttime LSTs combined. In the Lake Tahoe case, the mean and standard deviations are -0.05K and 0.53K for the daytime LSTs, 0.07K and 0.58K for nighttime LSTs, and 0.01K and 0.56K for daytime and nighttime LSTs combined. In the Namco case, the mean deviation values are slightly larger (0.2-0.4K) and the standard deviation values are almost the same when we consider the LSTs in their whole range. If we choose the LSTs larger than 273.15K (excluding the LSTs for lake ice), the mean values reduce to 0.2-0.3K. In the Greenland snow/ice case, the mean deviation values range from -0.5K to -0.4K and the standard deviation values range from 0.8K to 1.1K when we consider the LSTs in their whole range. If we choose the LSTs larger than 260K, the mean deviation values reduce to the range of -0.27K to 0.002K. This means that the day/night LST algorithm work well when the LSTs are relatively high, especially in the melting reason. This indicates that the surface emissivities in bands 31 and 32 in the look-up table (LUT) used in the split-window algorithm match well to those retrieved by the day/night algorithm in the melting reason. When the LSTs at this site get lower, normally in the days in which the solar zenith angle are larger (lower solar elevation angle), the mean of the difference between LSTs retrieved from the two algorithms becomes larger. There are two possible reasons: large errors in the snow/ice emissivities in the LUT in the dry reason or large errors due to the day/night algorithm in lower solar elevation conditions. From the comparison results in cases of Lake Superior, Lake Tahoe, Namco (lake), and the snow/ice site in Greenland, we can see that the day/night LST algorithm works well in lakes and snow/ice fields at different elevations.

In the Gaize semi-arid case, the mean deviation values range from -1.9K to -1.6K and standard deviations around 0.7K. Comparing the broadband emissivity calculated from the band emissivities in the MOD11B1 product to the broadband emissivity calculated from the ground measurements in 2001-2003 indicates that they agree well with a mean deviation of 0.001 and standard deviation of 0.013 (Kaincun Wang, personal communications, detail results are given in a paper submitted to JGR). This indirectly confirms that the

LUT used in the split-window algorithm often overestimates the emissivities in bands 31 and 32 in semi-arid and arid regions so that it is necessary to use the day/night LST algorithm to retrieve surface emissivities and temperatures simultaneously. The LSTs in the V4 MOD11A1 and MOD11B1 products at the Amazon rain forest site are shown in Figures 8 and 9. As shown in Table III, the mean deviation values ranging from -1.4K to -1.3K indicate that the LST from the split-window algorithm is smaller due to the following possible reasons: errors in the mean and difference in band emissivities of bands 31 and 32 in the LUT, column water vapor values underestimated by the MODIS Atmospheric Profile product (MOD07), and/or errors from the day/night algorithm.

In order to address the concern on the use of the day/night algorithm in tropical regions where there are less clear-sky days, we analyzed the clear-sky days in the LSTs at latitude/longitude 5.0 ° S, 65.0 ° W in Amazon rain forest in V4 1km and 5km MODIS LST (MOD11A1 and MOD11B1) products in 2001-2003. The numbers in Table IV indicated that the day/night LST algorithm can be used globally (even in tropical regions) as long as pairs of clear-sky day and night MODIS observations exist within a reasonable period of days.

## 4. CONCLUSION

A quite large percentage (>10%) of MODIS pixels defined by the current MODIS cloudmask product as clear-sky at the 99% confidence may be actually cloud-contaminated in some areas, especially in high-elevation regions. The cloud-contaminated LSTs in the MODIS LST products may be well removed by a cloud-screen scheme with constraints on spatial and temporal variations in the clear-sky LSTs. This cloud-screen scheme has been tested at sites in lakes, snow/ice, Amazon rain forest and semi-arid regions. However, the cloud-screen scheme with temporal constraints will hold the release of daily MODIS LST products for up to 32 days, against the interest of users. The best approach is to improve the MODIS cloudmask product with thresholds that depend on surface elevation and emissivities. The MOD11B1 product is validated through comparing the LSTs retrieved by the day/night method to the LSTs in the MOD11A1 product that has been validated with in-situ measurement data in lakes, snow and agricultural fields in field campaigns conducted in 2000-2003. The mean and standard deviation values of the differences between the LSTs retrieved by these two methods are within 0.03K and 0.6K in Lake Superior and Lake Tahoe, 0.3K and 0.6K in Namco, and -0.4K and 0.97K in a snow/ice site at 63.0 ° N, 47.8 ° W in Greenland. The MOD11B1 product is also validated with ground-based measurement data at Gaize (32.3 ° N, 84.06 ° E, 4420m above sea level) in the western Tibet plateau through comparing the broadband emissivity calculated from the band emissivities in the MOD11B1 product to the broadband emissivity calculated from the ground measurements in 2001-2003 (the mean and standard deviation are 0.001 and 0.013, respectively). The statistics of clear-sky days in the LSTs at latitude/longitude 5.0 ° S, 65.0 ° W in Amazon rain forest in V4 1km and 5km MODIS LST (MOD11A1 and MOD11B1) products in 2001-2003 indicated that the day/night LST algorithm can be used globally as long as pairs of clear-sky day and night MODIS observations exist within a reasonable period of days.

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## REFERENCES

Irbe, G. J., *Great Lakes Surface Water Temperature Climatology*, Ottawa: Canadian Government Publishing Centre, 1992.

Malm, J. and L. Jönsson, ‘‘Water surface temperature characteristics and thermal bar evolution during Spring in Lake Ladoga,’’ *Remote Sens. Environ.*, vol. 48, pp. 332-338, 1994.

Malm, J. and S. Zilitinkevich, ‘‘Temperature distribution and current system in a convectively mixed lake,’’ *Boundary-Layer Meteorol.*, vol. 71, pp. 219-234, 1994.

Wan, Z. and J. Dozier, ‘‘A generalized split-window algorithm for retrieving land-surface temperature from space,’’ *IEEE Trans. Geosci. Remote Sens.*, vol. 34, no. 4, pp. 892-905, 1996.

Wan, Z. and Z.-L. Li, ‘‘A physics-based algorithm for retrieving land-surface emissivity and temperature from EOS/MODIS data,’’ *IEEE Trans. Geosci. Remote Sens.*, vol. 35, no. 4, pp. 980-996, 1997.

Wan, Z., Y. Zhang, Q. Zhang, and Z.-L. Li, ‘‘Quality assessment and validation of the MODIS global land-surface temperature,’’ *Int. J. Remote Sens.*, vol. 25, no. 1, pp. 261-274, 2004.

Wan, Z., Y. Zhang, Q. Zhang, and Z.-L. Li, ‘‘Validation of the land-surface temperature products retrieved from Terra Moderate Resolution Imaging Spectroradiometer data,’’ *Remote Sens. Environ.*, vol. 83, pp. 163-180, 2002.

TABLE I. The change in number of LSTs at one point in Lake Tahoe and Namco (lake) in the V3 and V4 1km MODIS LST (MOD11A1) products in 2002 after applying the cloud-screen scheme with constraints on spatial and temporal variations.

| N | $(\delta T)_S$ | $(\delta T)_T$ | Lake Tahoe (39.101 °N, 120.04 °W) in V3 daytime | Lake Tahoe in V3 nighttime | Lake Tahoe in V4 daytime | Lake Tahoe in V4 nighttime | Namco (30.69 °N, 90.53 °E) in V3 daytime | Namco in V3 nighttime | Namco in V4 daytime | Namco in V4 nighttime |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | 174 (351) | 39 (351) | 257 (355) | 202 (355) | 170 (353) | 102 (353) | 219 (355) | 223 (355) |
| 4 | | | 162 | 10 | 250 | 191 | 163 | 66 | 200 | 210 |
| 4 | 3.0 | | 162 | 10 | 249 | 187 | 160 | 65 | 193 | 177 |
| 4 | 3.0 | 3.0 | 159 | 10 | 240 | 184 | 156 | 47 | 177 | 135 |
| 1 | | 3.0 | 169 | 39 | 245 | 195 | 163 | 76 | 190 | 138 |

TABLE II. The change in number of LSTs at one point in each test site in the V4 5km MODIS LST (MOD11B1) products in 2003 after applying the cloud-screen scheme with constraints on spatial and temporal variations.

| N | $(\delta T)_S$ | $(\delta T)_T$ | (39.101 °N, 120.04 °W) in Lake Tahoe daytime | in Lake Tahoe nighttime | (30.69 °N, 90.53 °E) in Namco daytime | in Namco nighttime | (63.0 °N, 47.8 °W) in Greenland daytime | in Greenland nighttime | (32.3 °N, 84.06 °E) in Gaize, Tibet daytime | in Gaize, Tibet nighttime |
|---|---|---|---|---|---|---|---|---|---|---|
| 4 | | | 264 (356) | 291 (356) | 196 (356) | 193 (356) | 145 (356) | 174 (356) | 246 (356) | 216 (356) |
| 4 | 3.0 | | 242 | 231 | 160 | 144 | | | | |
| 4 | 3.0 | 3.0 | 230 | 221 | 151 | 132 | | | | |
| 4 | 3.0 | | | | | | 121 | 121 | | |
| 4 | 3.0 | 4.0 | | | | | 103 | 81 | | |
| 4 | 5.0 | | | | | | | | 181 | |
| 4 | 5.0 | 10.0 | | | | | | | 178 | |
| 4 | 4.0 | | | | | | | | | 193 |
| 4 | 4.0 | 8.0 | | | | | | | | 193 |

TABLE III. The mean and standard deviation values of the differences between LST values retrieved by the generalized split-window and day/night methods at test sites in lakes, snow/ice, Amazon rain forest and semi-arid regions in 2003.

| site | lat, lon (°) | difference in daytime LSTs mean (K) | difference in daytime LSTs std dev (K) | difference in nighttime LSTs mean (K) | difference in nighttime LSTs std dev (K) | difference in day and night LSTs mean (K) | difference in day and night LSTs std dev (K) |
|---|---|---|---|---|---|---|---|
| Lake Superior, MI | 47.25, -87.22 | 0.02 | 0.54 | 0.06 | 0.55 | 0.03 | 0.55 |
| Lake Tahoe, CA | 39.101, -120.04 | -0.05 | 0.53 | 0.07 | 0.58 | 0.01 | 0.56 |
| Namco (lake), Tibet | 30.69, 90.53 | 0.22 | 0.58 | 0.41 | 0.55 | 0.31 | 0.58 |
| Namco (LST > 273.15K) | 30.69, 90.53 | 0.21 | 0.58 | 0.32 | 0.56 | 0.26 | 0.57 |
| Greenland (snow/ice) | 63.0, -47.8 | -0.49 | 0.75 | -0.37 | 1.11 | -0.44 | 0.97 |
| Greenland (LST > 260K) | 63.0, -47.8 | -0.27 | 0.73 | 0.002 | 1.05 | -0.18 | 0.88 |
| Amazon (rain forest) | -5.0, -65.0 | -1.28 | 0.66 | -1.38 | 0.51 | -1.31 | 0.62 |
| Gaize, Tibet (semi-arid) | 32.30, 84.06 | -1.89 | 0.70 | -1.62 | 0.65 | -1.75 | 0.68 |

TABLE IV. The change in number of LSTs at 5.0°S, 65.0°W in Amazon rain forest in V4 1km and 5km MODIS LST (MOD11A1 and MOD11B1) products in 2001-2003 after applying the cloud-screen scheme with constraints on spatial and temporal variations.

| N | $(\delta T)_S$ | $(\delta T)_T$ | 2001 MOD11A1 day | 2001 MOD11A1 night | 2001 MOD11B1 day | 2001 MOD11B1 night | 2002 MOD11A1 day | 2002 MOD11A1 night | 2002 MOD11B1 day | 2002 MOD11B1 night | 2003 MOD11A1 day | 2003 MOD11A1 night | 2003 MOD11B1 day | 2003 MOD11B1 night |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 3 | | | 53 | 15 | 74 | 29 | 65 | 16 | 77 | 36 | 62 | 22 | 71 | 30 |
| 3 | 3.0 | | 53 | 15 | 62 | 18 | 65 | 16 | 62 | 25 | 62 | 22 | 69 | 30 |
| 3 | 3.0 | 3.0 | 45 | 15 | 60 | 18 | 57 | 16 | 58 | 25 | 56 | 20 | 67 | 29 |

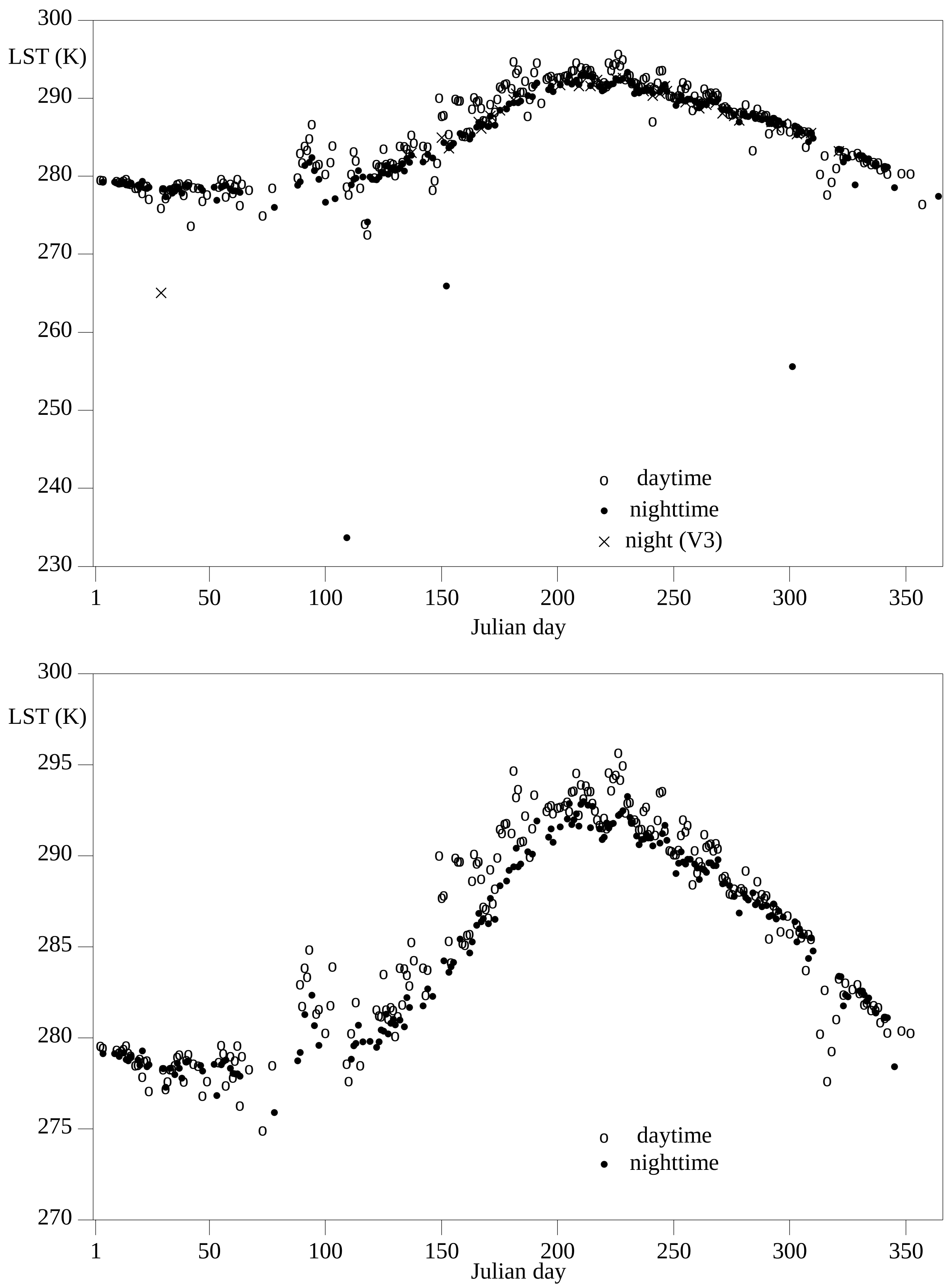



Figure 1, The daytime and nighttime LSTs near the center of Lake Tahoe in the V3 and V4 MOD11A1 products in 2002 before (top) and after (bottom) applying the cloud-screen scheme.

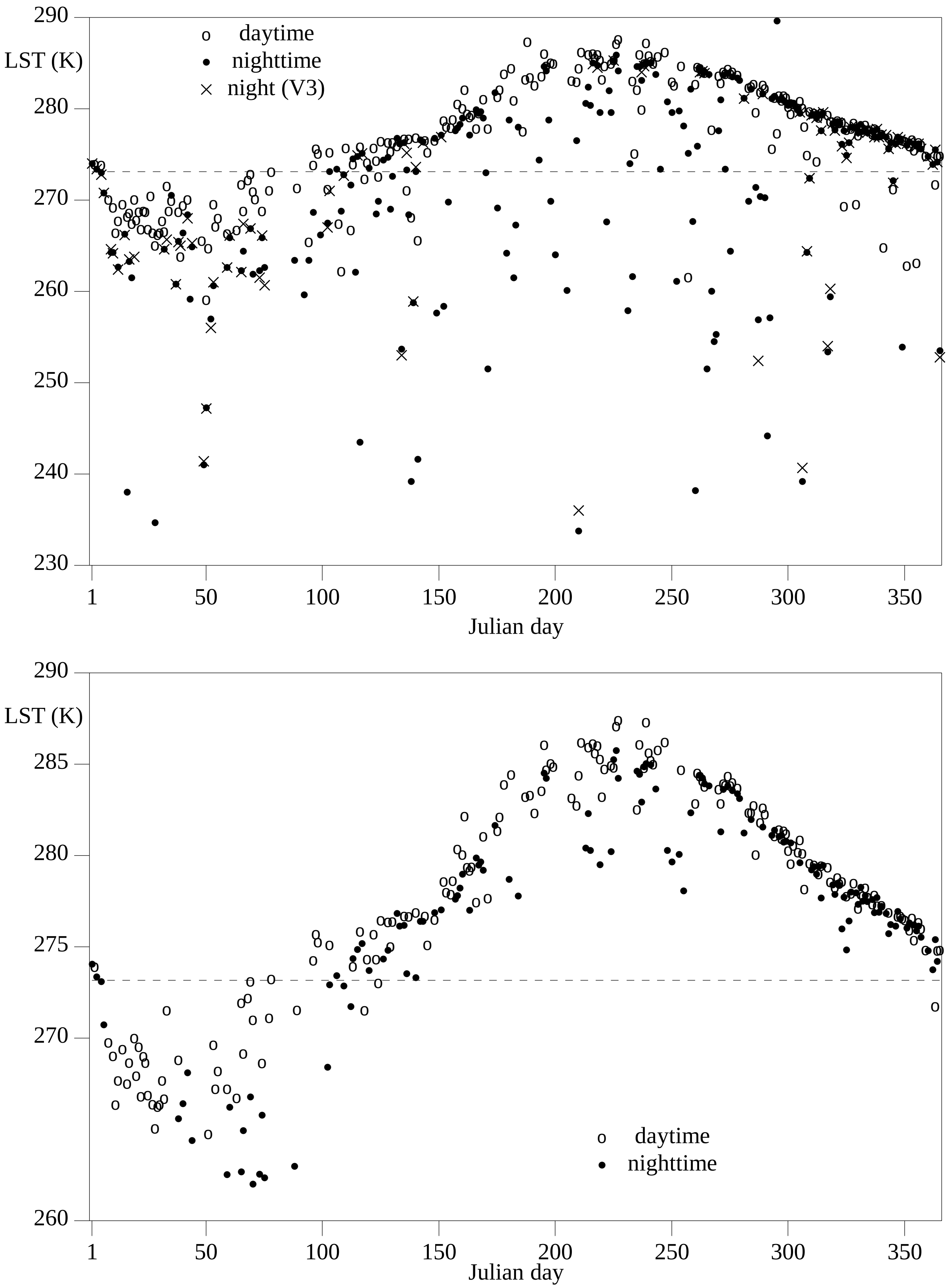



Figure 2, The daytime and nighttime LSTs at 30.69°N, 90.53°E in Namco (lake) in the V3 and V4 MOD11A1 products in 2002 before (top) and after (bottom) applying the cloud-screen scheme.

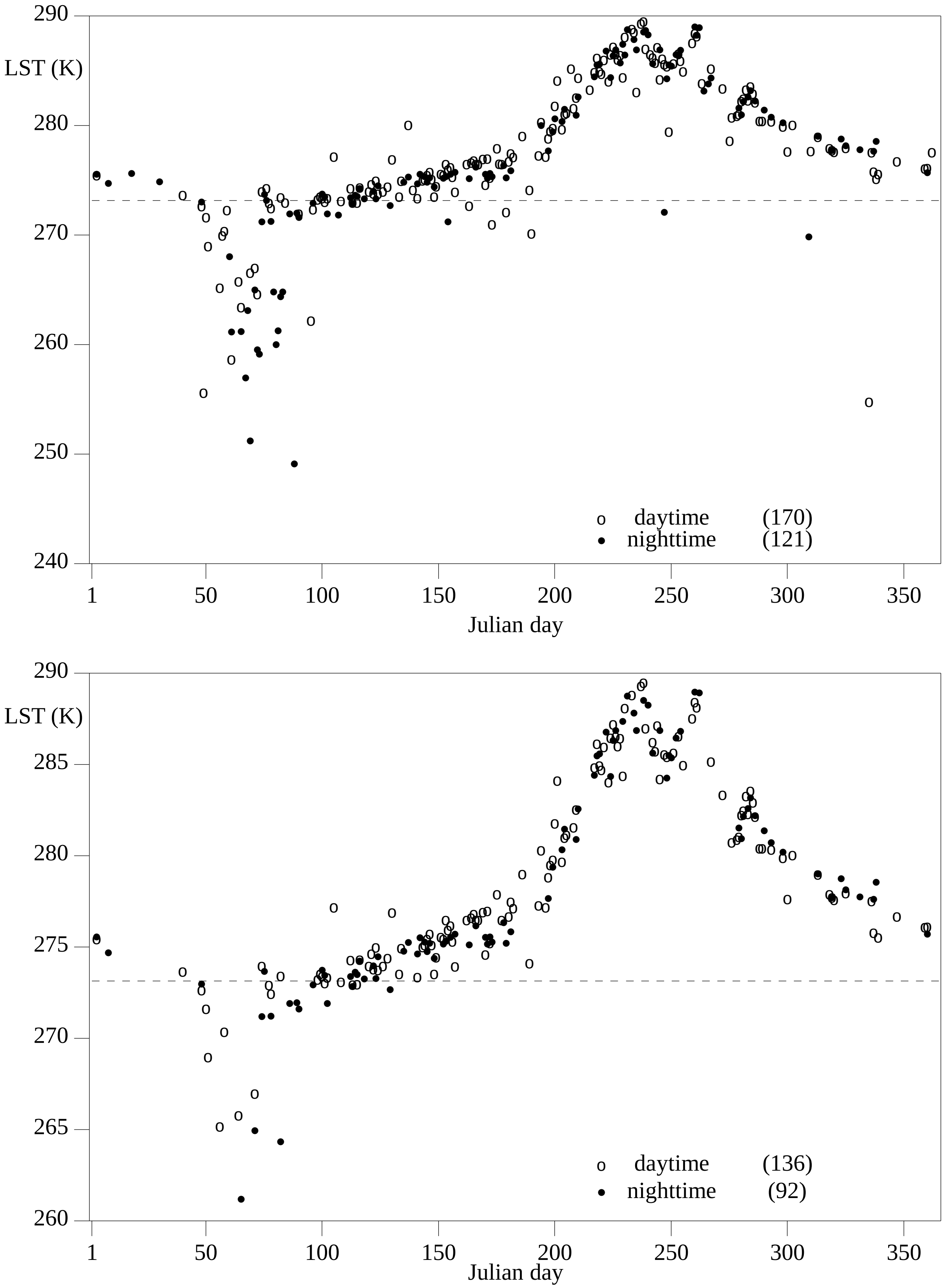
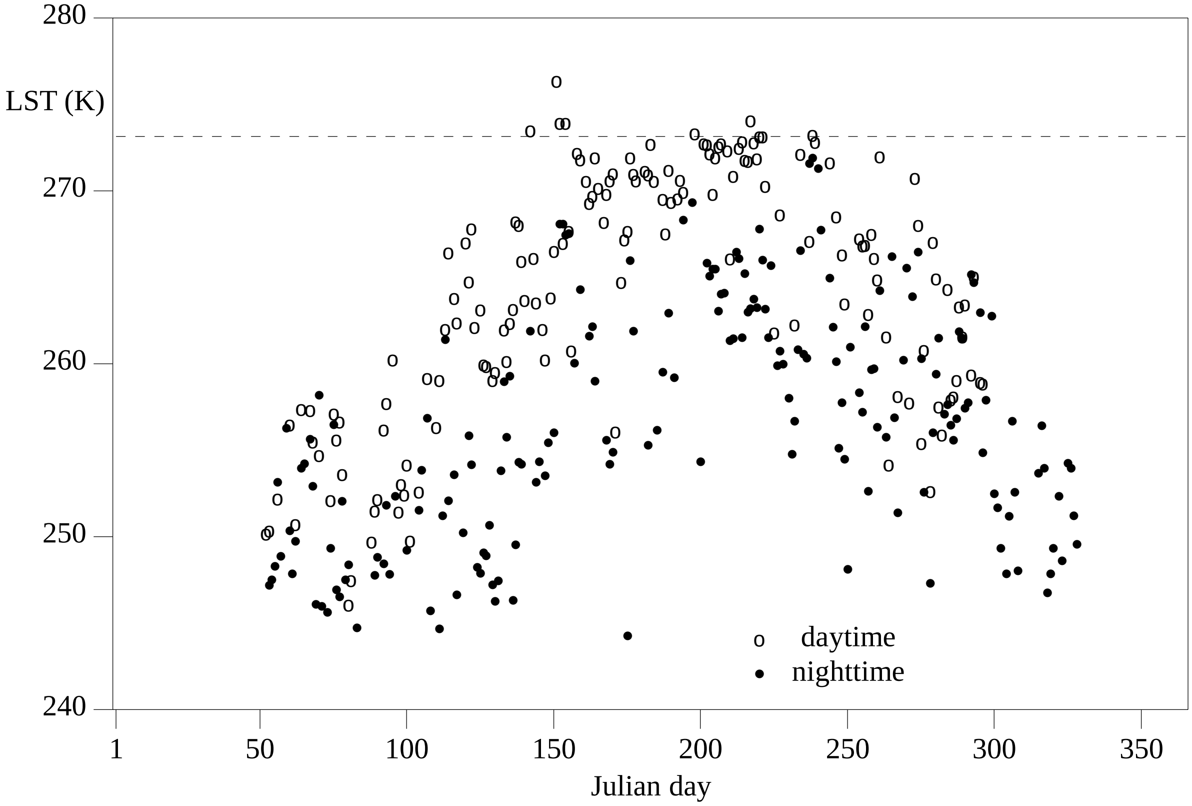



Figure 3, The daytime and nighttime LSTs at 47.25 ° N, 87.22 ° W in Lake Superior in the V4 MOD11B1 product in 2003 before (top) and after (bottom) applying the cloud-screen scheme.



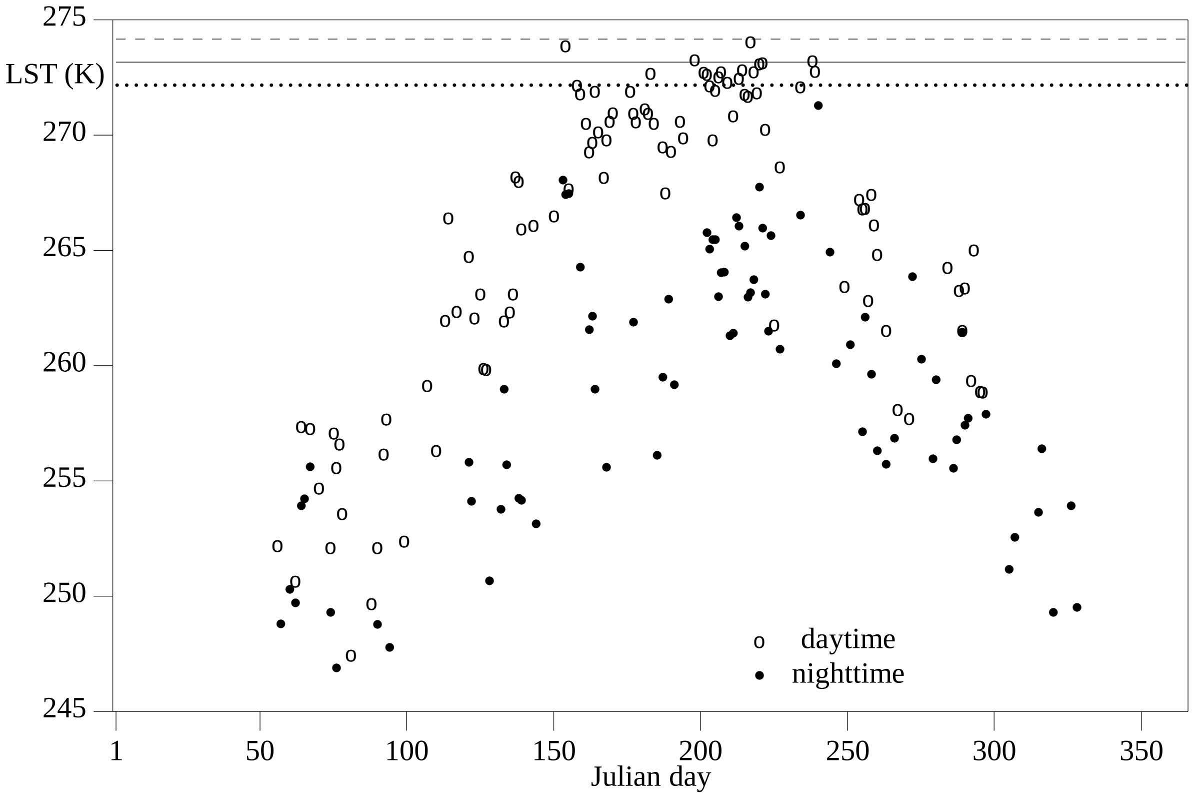
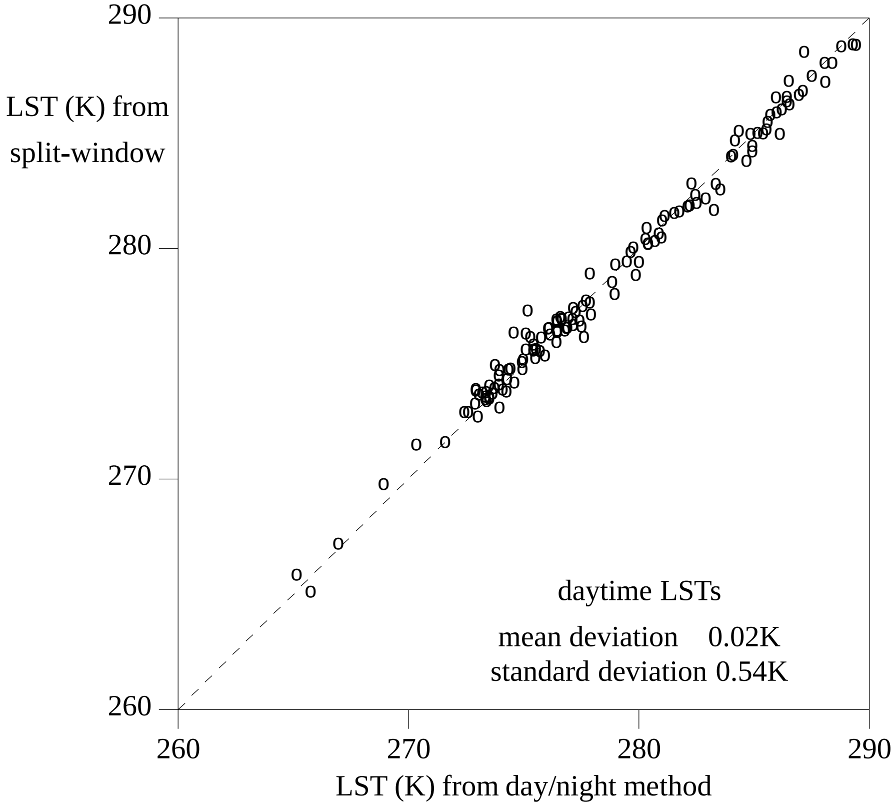




Figure 4, The daytime and nighttime LSTs at 63.0 ° N, 47.8 ° W in Greenland in the V4 MOD11B1 product in 2003 before (top) and after (bottom) applying the cloud-screen scheme.



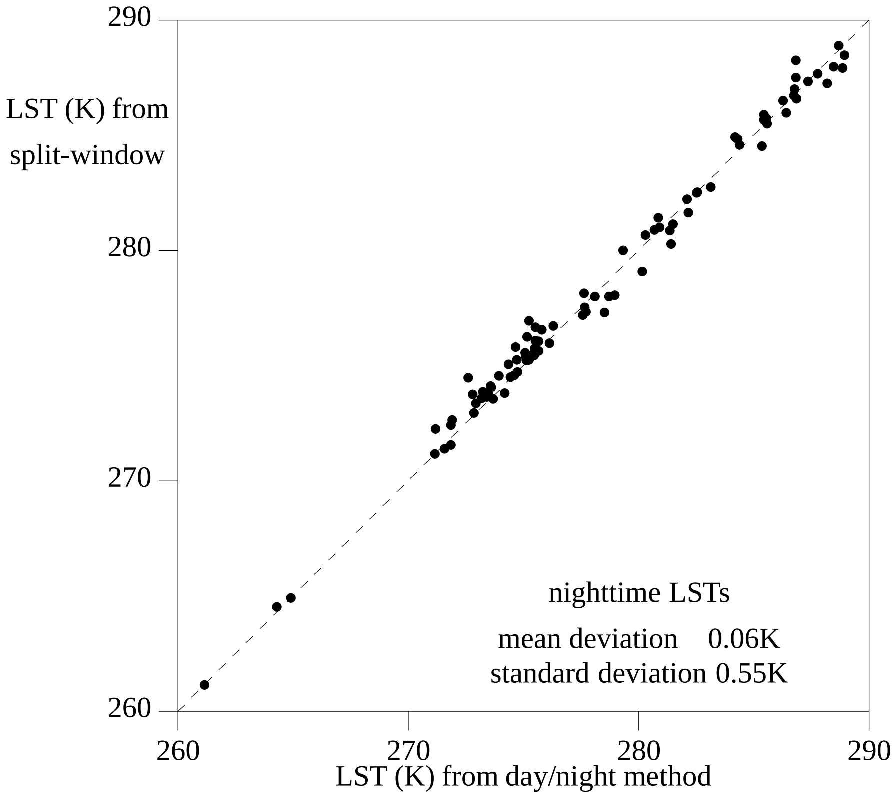




Figure 5, Comparison between the LSTs retrieved by the split-window method and the day/night LST method in the V4 MOD11B1 product in 2003 in Lake Superior in day (top) and night (bottom).

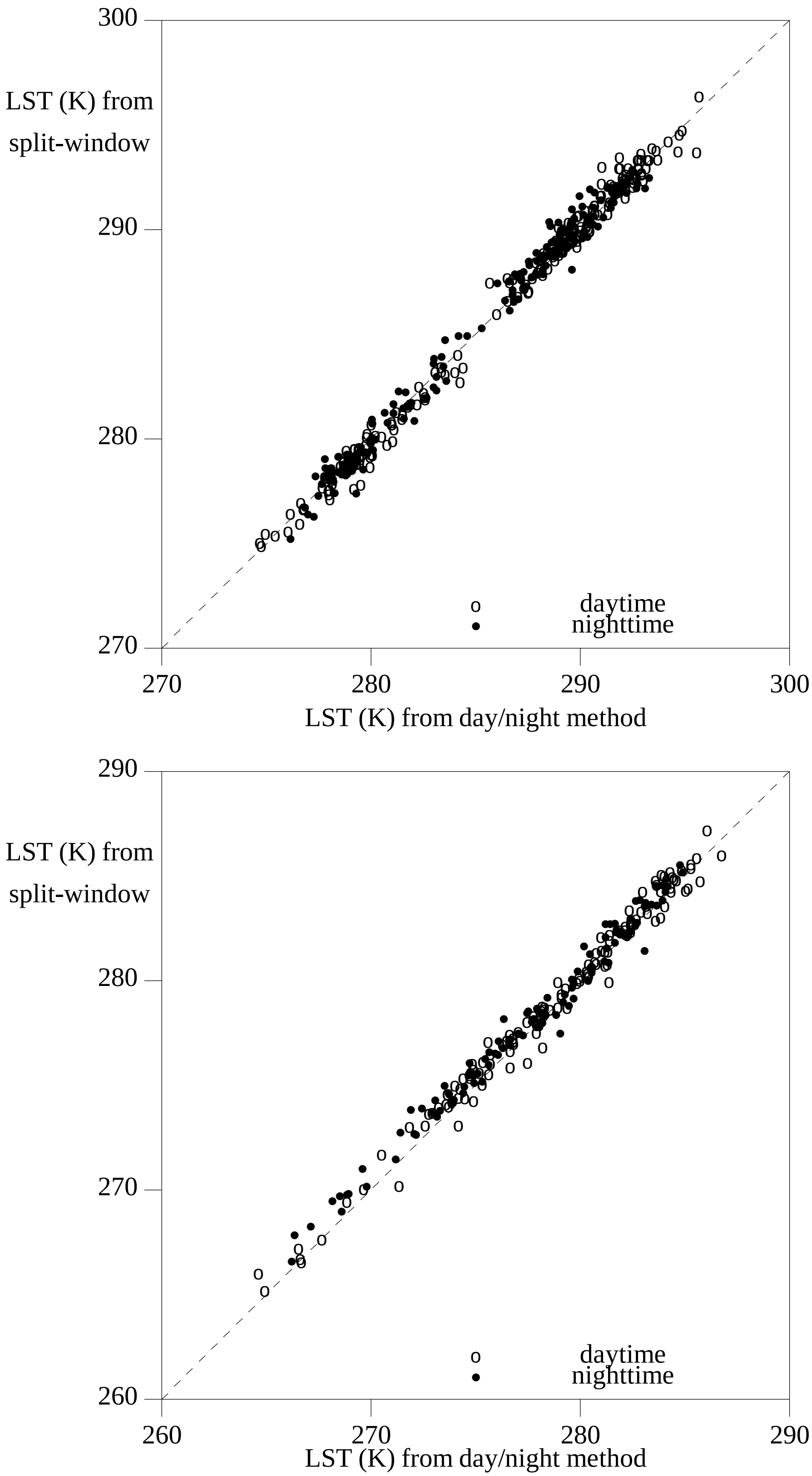



Figure 6, Comparison between the LSTs retrieved by the day/night LST method and the generalized split-window method in the V4 MOD11B1 product in 2003 in Lake Tahoe (top) and Namco (bottom).

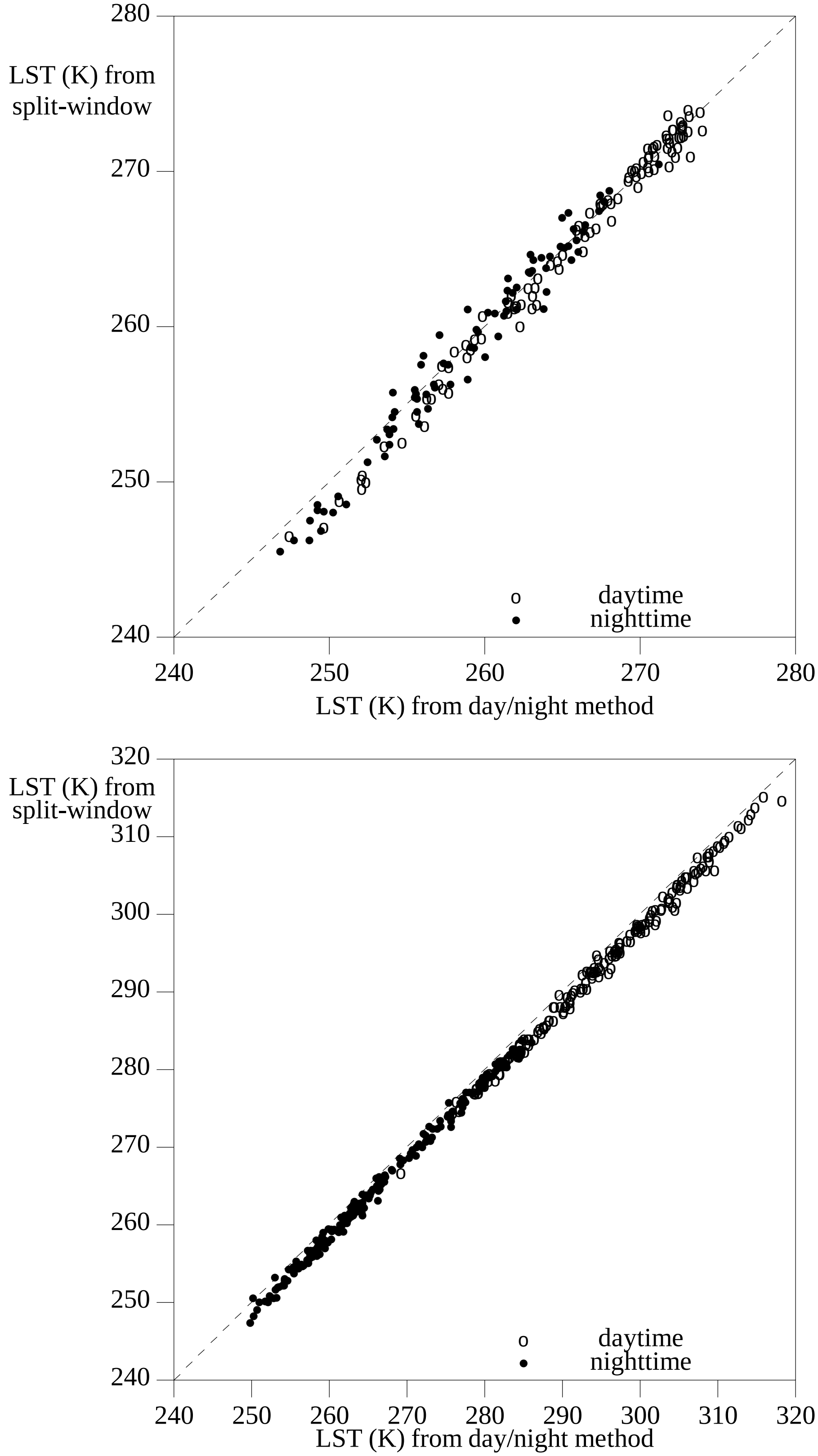



Figure 7, Comparison between the LSTs retrieved by the day/night LST method and the generalized split-window method in the MOD11B1 product in 2003 in Greenland (top) and at Gaize, Tibet (bottom).

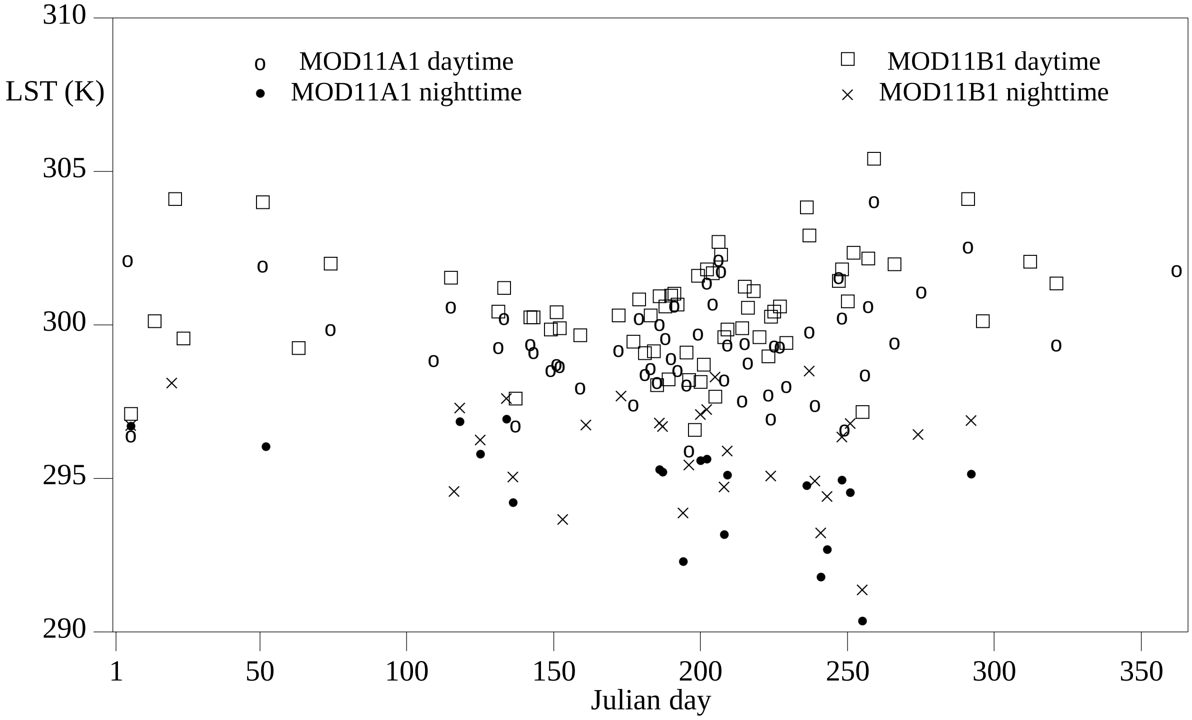



Figure 8, The LSTs in the V4 MOD11A1 and MOD11B1 products at a site in Amazon rain forest in 2003.

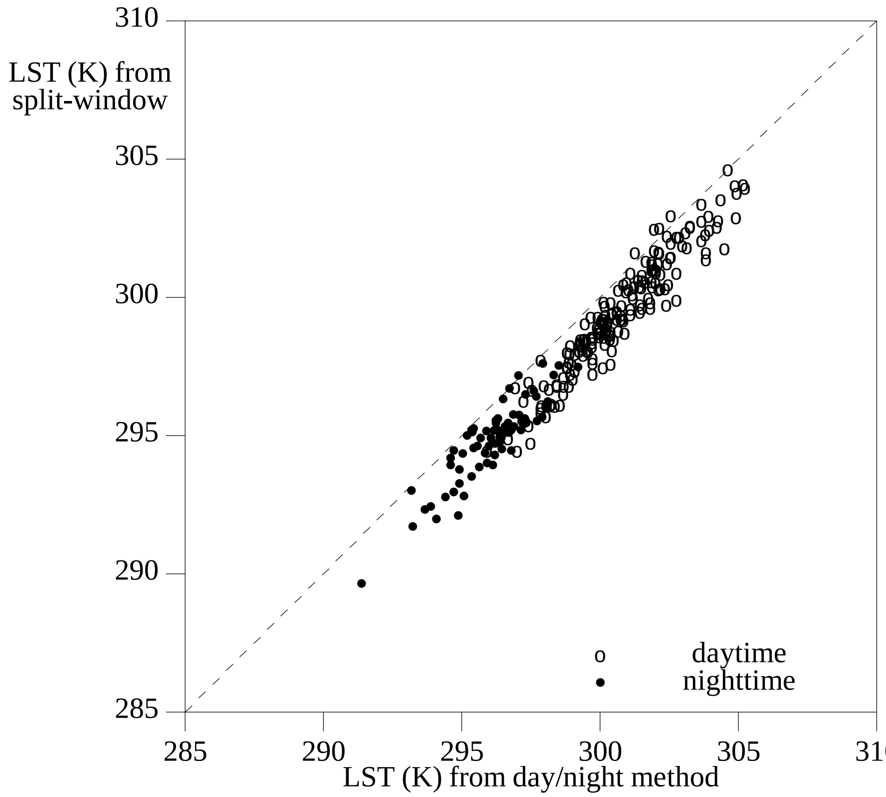



Figure 9, Comparison between the LSTs retrieved by the day/night LST method and the generalized split-window method in the V4 MOD11B1 product in 2003 at 5.0 ° S, 65.0 ° W in Amazon rain forest.